some, with the dips at 135° and 315°, turn clockwise; and still others, with the dips at 0° and 180° or 90° and 270°, show no directed motion. But unlike the turbine, whose symmetry breaking is random, the direction of any given motor can be controlled by adjusting the direction of the field.

Full speed ahead

The *Nature* motor can perform work against a load: The researchers attached the DNA blade to a molecular torsion spring, and they showed that the motor's rotation winds up the spring and stores energy that can be released later. That capability hasn't been tested with the *Nature Physics* turbine—"That would be a fascinating avenue for future experiments," says Golestanian—but just dragging the 500 nm DNA bundle through the surrounding liquid also takes work.

Indeed, both rotor blades were longer, and therefore slower, than they'd likely be in any future molecular-machinery application. They needed to be as long as they were so the researchers could attach fluorescent molecules to the ends of the blades and watch the rotation in real time. The resulting speeds, up to 20 rotations per second for the turbine and four rotations per second for the motor, were slower than those of biomolecular rotors by a factor of 10–100. But shortening the blades would probably make them faster.

Research on synthetic molecular machines is still in the exploratory stages, but researchers have ambitious dreams. On the wish list of what might be possible: docking rotors to biological membranes instead of synthetic ones, finding a way to reverse the turbine action to pump ion currents instead of being driven by them, and using the rotors to mechanically assemble molecules like ATP synthase does. Dietz says, "It feels like with one more missing piece, we could make something really useful, straight out of science fiction."

Johanna Miller

References

1. See, for example, S. Borsley et al., *Nature* **604**, 80 (2022).
2. X. Shi et al., *Nat. Phys.* **18**, 1105 (2022).
3. A.-K. Pumm et al., *Nature* **607**, 492 (2022).
4. X. Shi et al., https://arxiv.org/abs/2206.06612.
5. M. O. Magnasco, *Phys. Rev. Lett.* **71**, 1477 (1993).

Giant meteorites could be responsible for Earth's continents

The isotopic composition of ancient Australian rocks may answer a long-standing question about early Earth.

The Pilbara craton, in the Pilbara region of Western Australia, is the best-preserved remnant of Earth's ancient continental crust (see figure 1a). It formed during the Archean eon 4 billion to 2.5 billion years ago. At that time, Earth is believed to have had a water-covered primordial crust that was more or less a single, continuous shell around the mantle. Eventually, the primordial crust transformed into continental crust, which was later joined by its thinner and denser cousin, oceanic crust.

Most present-day oceanic crust is at most 200 million years old, and its for-

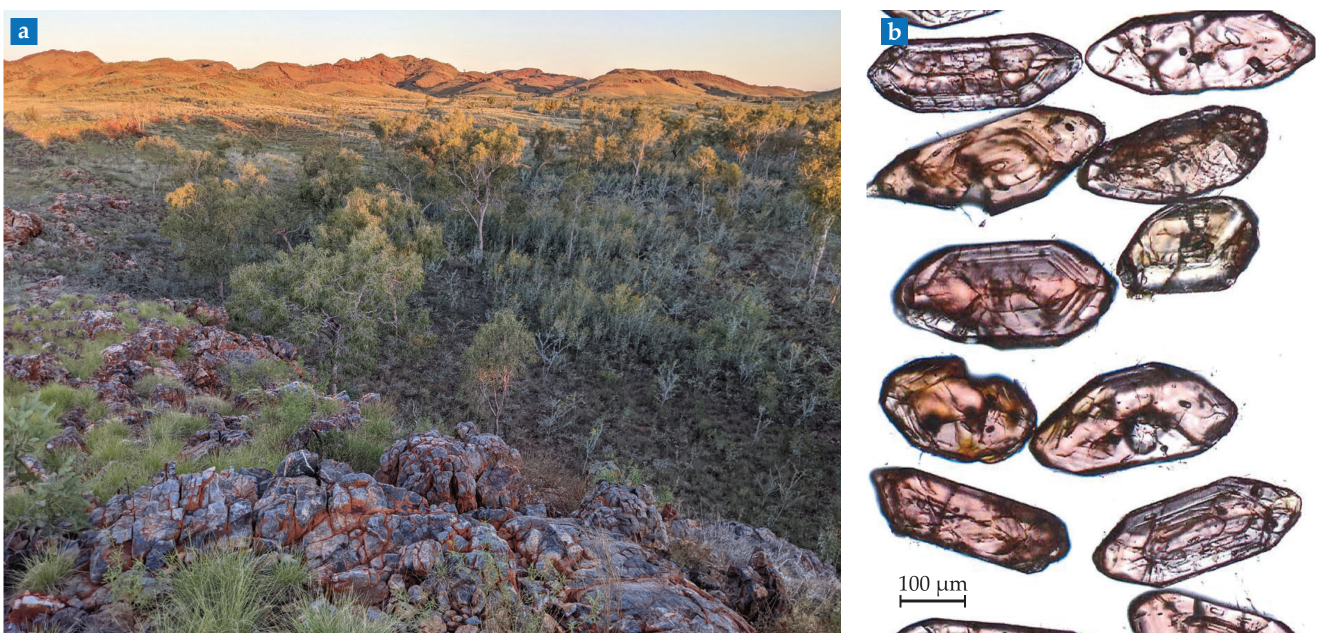

FIGURE 1. THE PILBARA REGION of Western Australia hosts the best-preserved fragment of Earth's ancient continental crust. **(a)** The Pilbara craton formed as far back as 3.6 billion years ago, around the same time as most of today's landmass. It is one of a handful of locations where geological processes between the rocks' formation and the present day haven't erased mineral markers of their origins. **(b)** Zircon grains extracted from Pilbara rocks are particularly useful measures of the craton's past because their composition reveals their age and the conditions at the time of their formation. (Images courtesy of Chris Kirkland.)

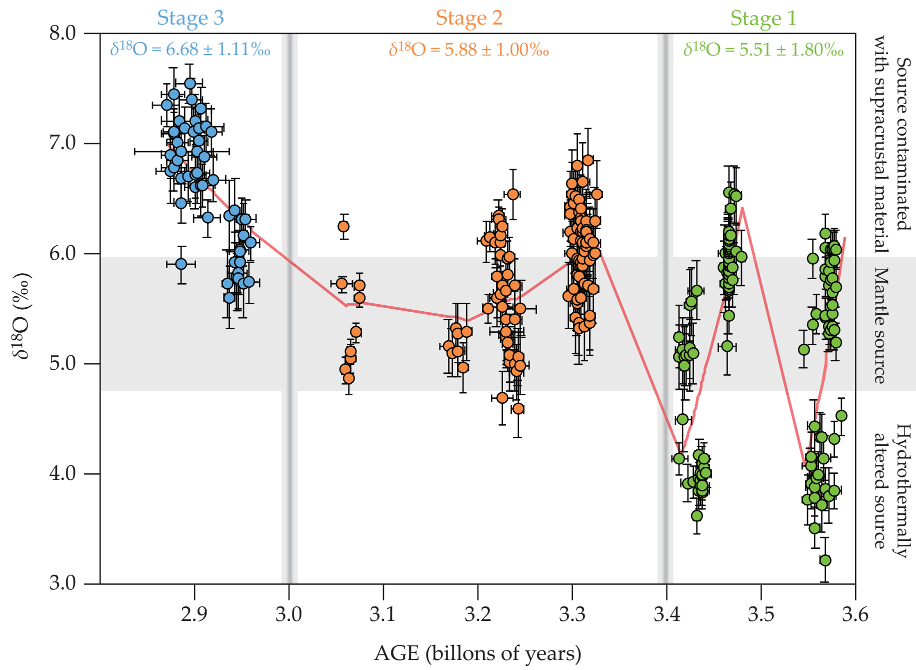

FIGURE 2. OXYGEN ISOTOPES in zircon reflect the source materials that formed the mineral. The ratio of ^{18}O to ^{16}O in secondary-ion mass spectroscopy measurements is compared with a standard reference of distilled seawater to find a relative difference $\delta^{18}O$ in parts per thousand (‰). A useful benchmark is the $\delta^{18}O$ of Earth's mantle (horizontal gray stripe). As indicated by a local regression fit (pink line), zircon grains from the Pilbara craton have $\delta^{18}O$ values that trend with decreasing age, given in stages separated by vertical gray lines, from lower than the mantle in stage 1 (green) to mantle-like in stage 2 (orange) to higher than the mantle by stage 3 (blue). A giant impact could explain the trend. (Adapted from ref. 2.)

mation is ongoing and well understood: When a gap opens between tectonic plates, magma bubbles up into the gap, cools, and spreads out from the initial ridge. Continental crust is much older; three-quarters of the present-day landmass worldwide formed in the Archean as did the Pilbara craton. Because the continents have been around so long, figuring out their genesis is a challenge. Earth's geological evolution gradually and often violently transforms and mixes continental crust until evidence of the distant past is erased.

Since the mid 1960s, one theory has argued that continents formed at the sites of collisions with asteroids tens or a couple hundred kilometers wide.[1] The resulting heating and excavation of the primordial crust would have triggered a sequence of events in which the melted mantle swelled up and overfilled the crater to create a plateau. That seed would then have grown into a continent.

The idea makes chronological sense; the solar system saw a barrage of asteroids around 3.9 billion years ago, a period known as the Late Heavy Bombardment. The Moon's craters are evidence of that period (see the article by Brett Denevi, Physics Today, June 2017, page 38). Earth surely underwent a more ferocious onslaught, as it has more surface area and a larger mass to draw in objects, but the evidence has been limited. And no concrete proof has connected the Late Heavy Bombardment to the formation of continents.

Now Tim Johnson of Curtin University in Australia and his colleagues have found support for the theory that continents formed at the sites of giant impacts.[2] They show that the isotopic composition of Pilbara craton rocks matches what's expected if an asteroid hit the region. Their description of how the craton emerged may explain not only the Pilbara's formation but the making of Earth's continents.

Rock of ages

Johnson, who hails from the UK, arrived in Western Australia in early 2014, just after he had begun thinking deeply about early Earth—that is, the first billion or so years of its four-and-a-half-billion-year existence. He soon met Hugh Smithies of the Geological Survey of Western Australia (GSWA), a division of the state's Department of Mines, Industry Regulation, and Safety. The GSWA was founded over a century ago to gather geological information.

Smithies had long been researching ancient rocks from the Pilbara craton and elsewhere in Western Australia. Those rocks offered an ideal way to study early Earth. Over the course of nearly a decade, Smithies, Johnson, and their collaborators teamed up on a series of projects that used data from Pilbara craton samples. The new study, a culmination of that work, started when Smithies and Yongjun Lu, also from the GSWA, went to Curtin University to discuss some intriguing recent data with Johnson and his colleague Chris Kirkland, an expert on isotope geology.

The team used secondary-ion mass spectroscopy on 26 Pilbara craton rocks that were 2.9–3.6 billion years old. The measurements focused on grains of the magmatic mineral zircon (shown in figure 1b), which is common in igneous rocks. Such grains are useful because they can be dated through the decay of the material's radioactive uranium. What's more, zircon's compositional ratio of oxygen-18 to oxygen-16 isotopes provides a snapshot of its environment—source materials, temperature, and so on—at the time it formed. For the Pilbara samples, the ratios showed three distinct ranges of values that depended on the age of the zircon, as shown in figure 2.

The team wondered whether a giant impact could explain the observation. A strong sign would be that the oldest zircon grains show evidence of forming not from mantle-derived magma originating deeper in Earth but from surface materials melted together by the exceptional heat and compression of an asteroid impact. Such a collision would also produce a whole series of events with potentially discernible influences on the oxygen isotope ratios.

Watered down

The researchers investigated the $^{18}O/^{16}O$ isotope ratio of the zircon samples relative to Vienna Standard Mean Ocean Water, a pure-water benchmark distilled from ocean water gathered from around the globe (see PHYSICS TODAY online, "Setting standards with old rocks and ocean water," 6 December 2018). The zircon's ratio is then expressed as a relative difference $\delta^{18}O$, typically in parts per thousand (‰).

A useful point of comparison is Earth's mantle: Its $\delta^{18}O$, shown as a gray horizontal stripe in figure 2, is reasonably homogenous and has been stable over time. The mantle serves as an oxygen isotope reservoir, and minerals formed there will more or less share the same $\delta^{18}O$. For minerals formed outside the mantle, $\delta^{18}O$ generally depends on the environmental temperatures.[3] The low-temperature hydrothermal interactions on Earth's surface lead to materials with higher $\delta^{18}O$ than the mantle. Those just below the surface have higher-temperature rock–water interactions and lower $\delta^{18}O$.

Johnson and his colleagues found that for zircon grains older than 3.4 billion years, which they named stage 1, a third have ratios less than that of the mantle. Zircon ages 3.0–3.4 billion years (stage 2) have a higher median $\delta^{18}O$ than that in stage 1, with more than half of the ratios falling in the range expected for the mantle and nearly all the rest higher. For the youngest zircon, with ages less than 3.0 billion years (stage 3), more than three-fourths have $\delta^{18}O$ higher than the mantle.

Johnson and his colleagues argue that the data fit with what would be expected from a giant impact. The low $\delta^{18}O$ values in stage 1 indicate a material source near Earth's surface that was hydrothermally altered at high temperatures, as expected if a burning meteorite crashed into, cracked, and melted a primordial crust covered with ocean water.

The heating and compression from such an impact would spread down to the mantle, which would melt and eventually swell up to fill the crater until it becomes a plateau. That continental nucleus would have crystallizing magmas at its base, which would melt to produce granites with the mantle-like isotope ratios seen in stage 2. Finally, in stage 3, dense near-surface rocks, with their higher $\delta^{18}O$, would sink and end up in a process of intracrustal recycling sometimes called sagduction, akin to subduction but without tectonic plates. From there that continental nucleus would grow.

Additional evidence supports the idea that giant impacts occurred in the region. The Pilbara craton has what's known as spherule beds, a layer of spherical sediment droplets. Spherules are commonly believed to arise from ejected liquid or vaporized rock from a giant impact. The oldest spherule beds in the Pilbara are about 3.4 billion years old, which reassuringly is the same age as a large cluster of low $\delta^{18}O$ zircon grains.

Johnson says that some researchers have been reluctant to accept that giant impacts shaped our planet in any appreciable way, so he suspects that the new work will face opposition in the community. "I'm hoping that the research will stimulate vigorous activity among several groups that will be keen to prove us wrong," Johnson says. "The early Earth is a very controversial scientific endeavor. We're talking about so long ago, and the rocks are so old and have undergone such an uncommonly violent subsequent history."

Any alternative explanation would need to fit the data as well as a giant impact does, though. Two popular alternative theories—that hot matter bubbled up from the mantle to form a continental seed or that plate tectonics were already at play in the Archean—both predict the oldest zircons would have origins from deep below the surface and thus have mantle-like $\delta^{18}O$ values.

Johnson and his colleagues' next step is to investigate other well-preserved ancient rocks in northwest Canada, southern Greenland, and a few other territories to see whether giant impacts could explain all continental masses, not just the Pilbara region. Their initial look at data from the Slave craton in Canada is promising.

Heather M. Hill

References

1. J. W. Salisbury, L. B. Ronca, *Nature* **210**, 669 (1966).
2. T. E. Johnson et al., *Nature* **608**, 330 (2022).
3. J. W. Valley et al., *Contrib. Mineral. Petrol.* **150**, 561 (2005).